Photonic Crystals and Tunable Time Delay

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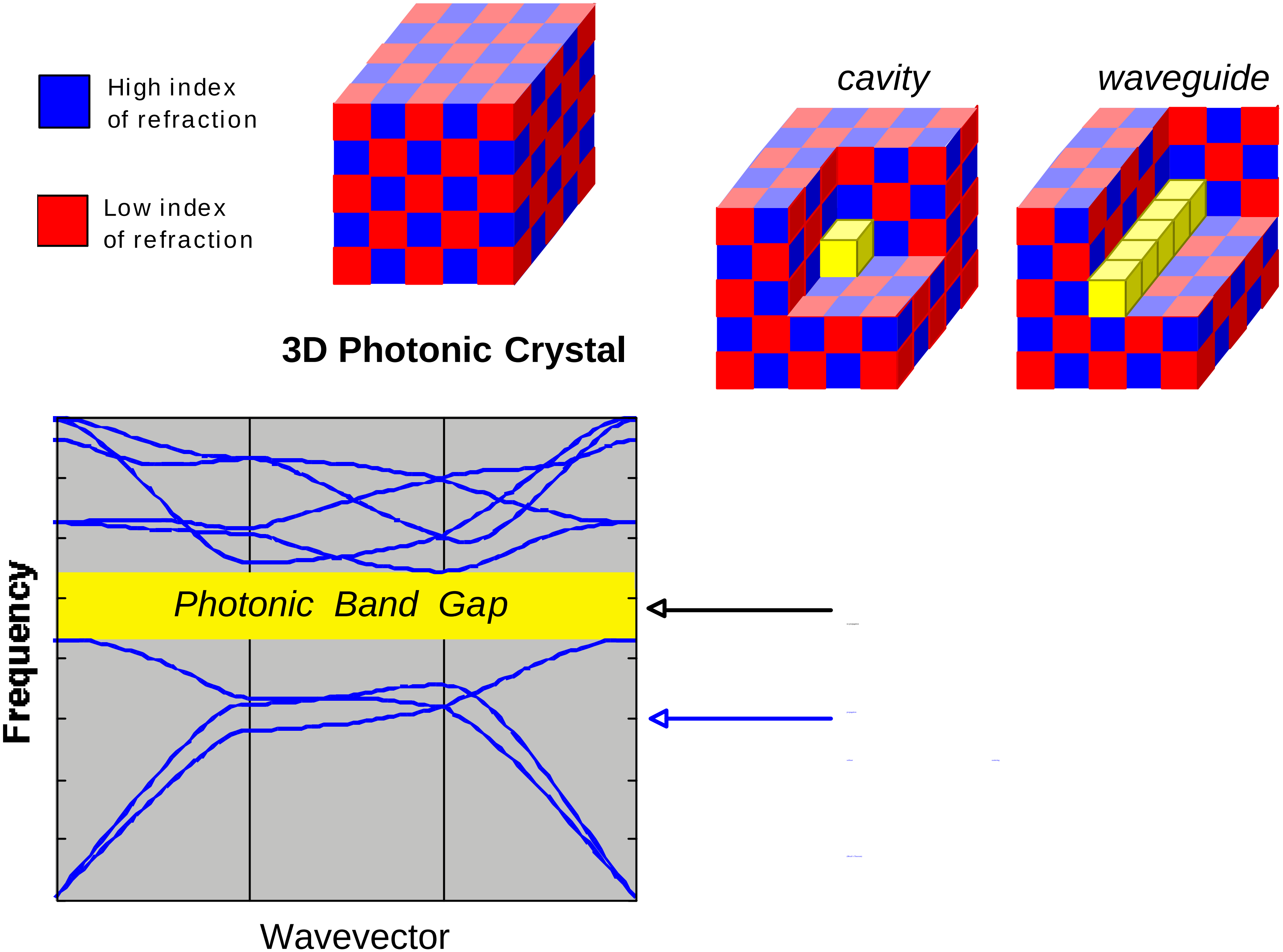
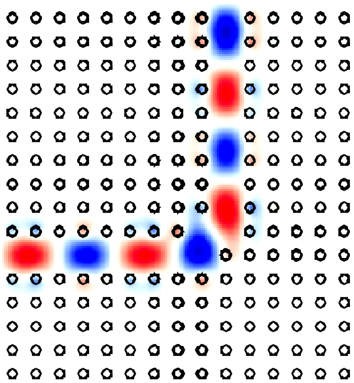
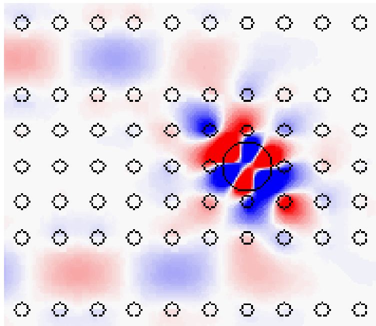
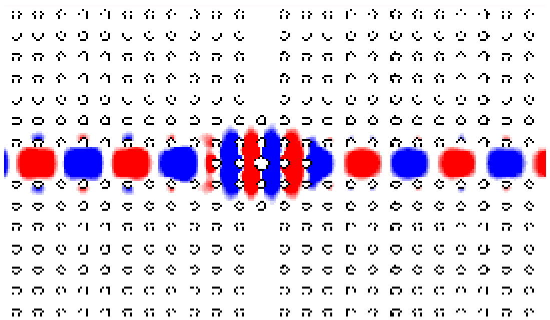

High index
of refraction
Low index
of refraction
3D Photonic Crystal
cavity
waveguide
Photonic Band Gap
Frequency
Wavevector



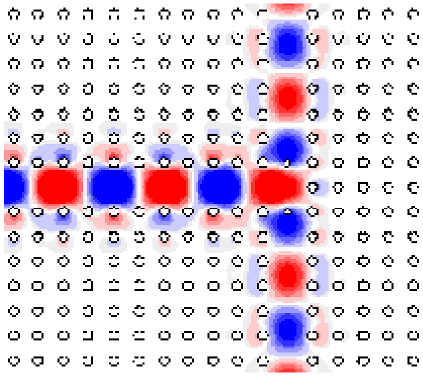
channel-drop filter



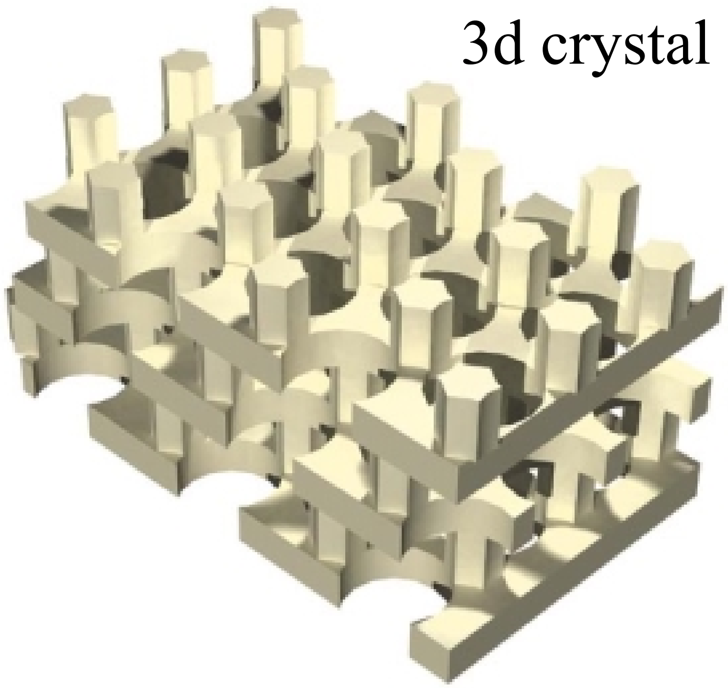
elimination of waveguide crosstalk



high transmission in wide-angle splitters

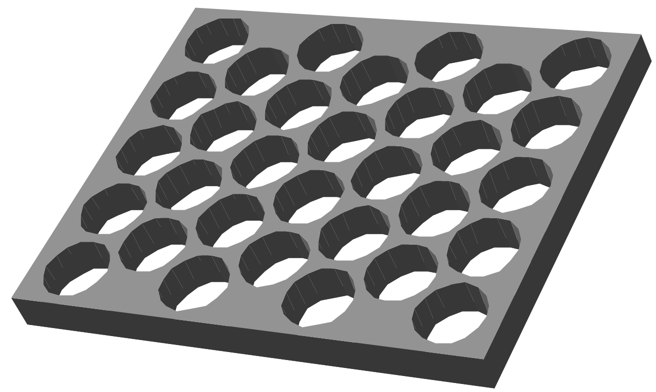


1D Scattering + Symmetry = Devices

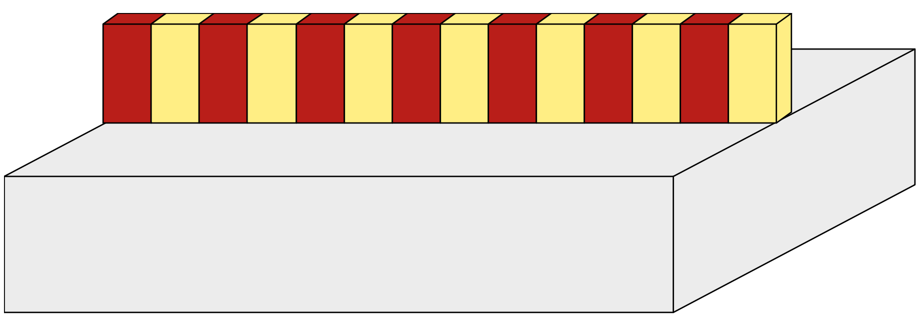


3d crystal (complete gap)

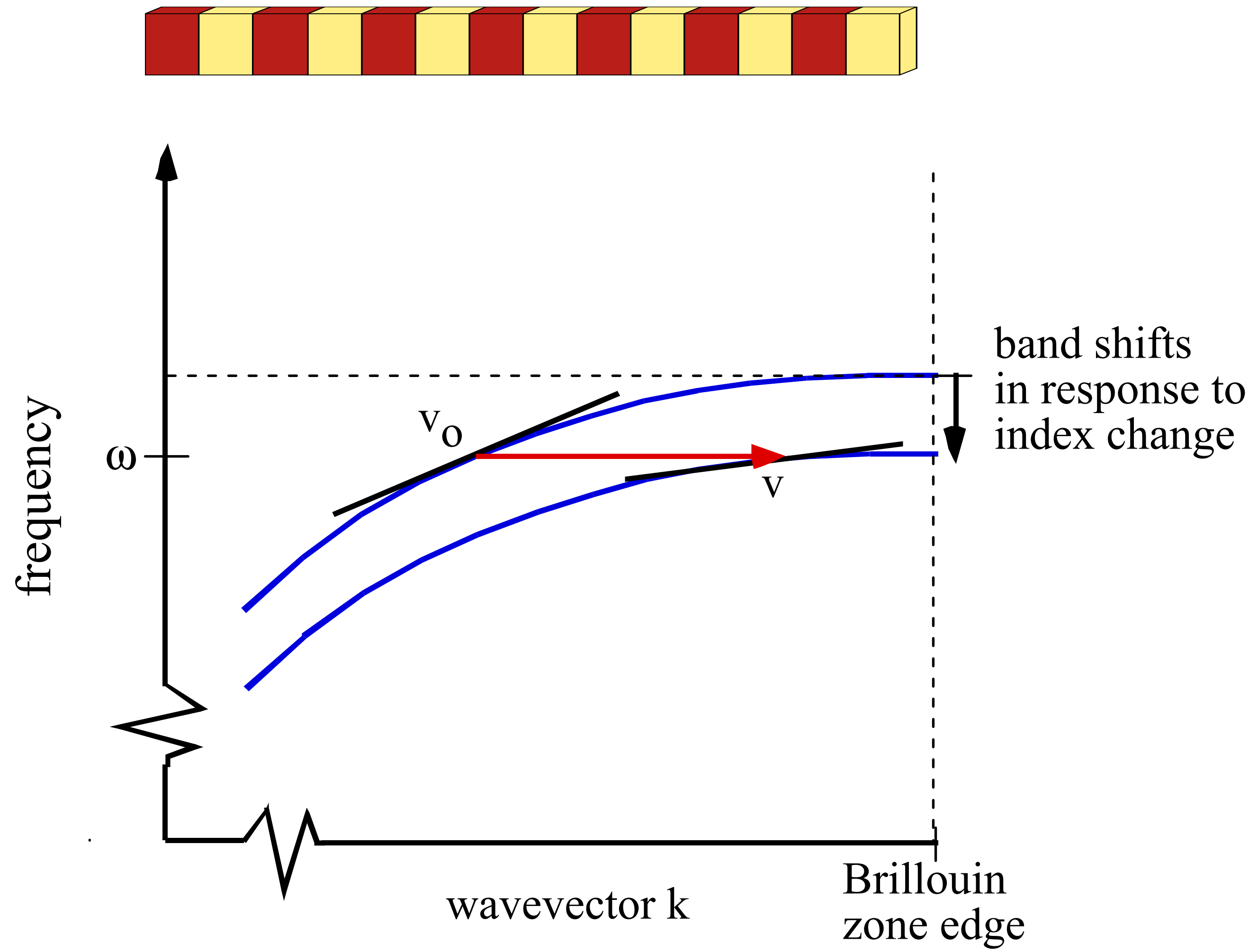
2d crystal "slab"



1d crystal, grating



Tunable Time Delay



Group-velocity dispersion *diverges* at the band edge.

Tunable Time Delay Devices

Want: ~ 10 GHz bandwidth, ΔT = 10ns tunable delay
~ 1% index shift $\Delta n / n$

Tunability
Dispersion tolerance

Gap size
Confinement strength

Losses

Tunability: a Figure of Merit

tunable delay

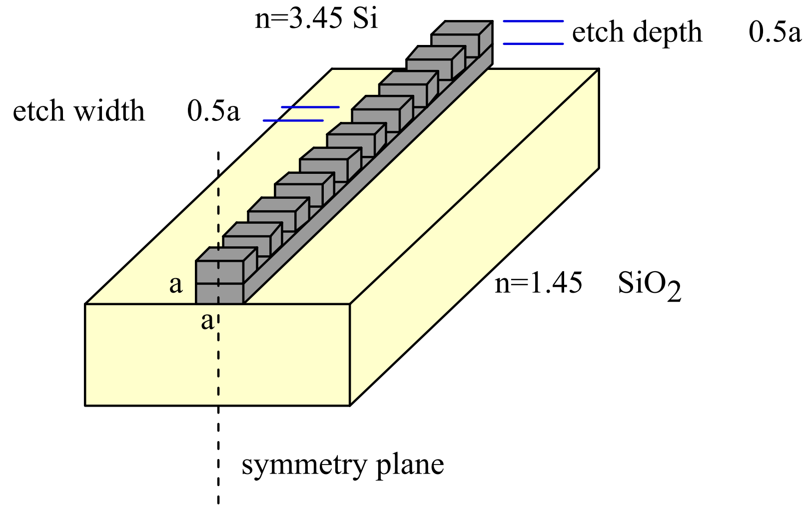
total delay

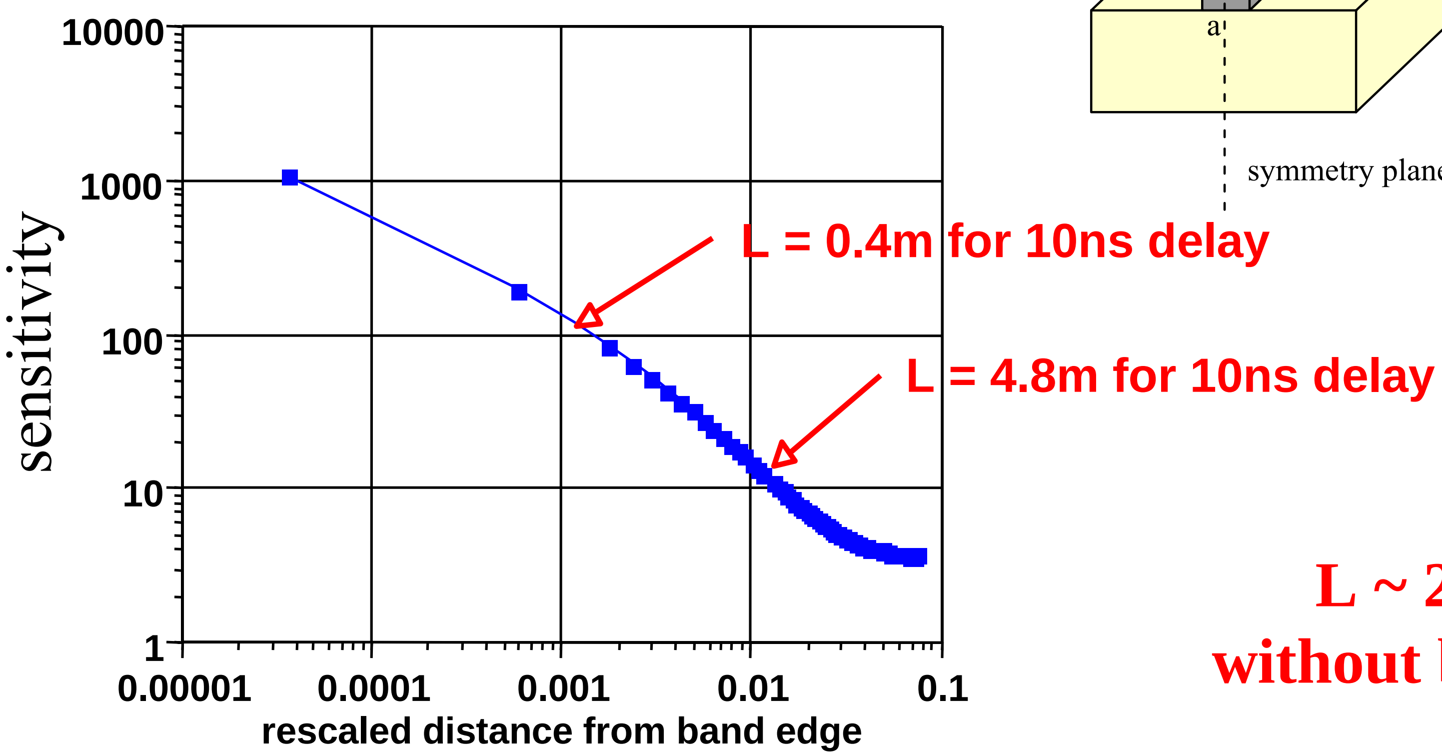
$\sim$ loss

$$\text{define sensitivity} = \frac{\dfrac{\Delta T}{T}}{\Delta n / n}$$

control strength

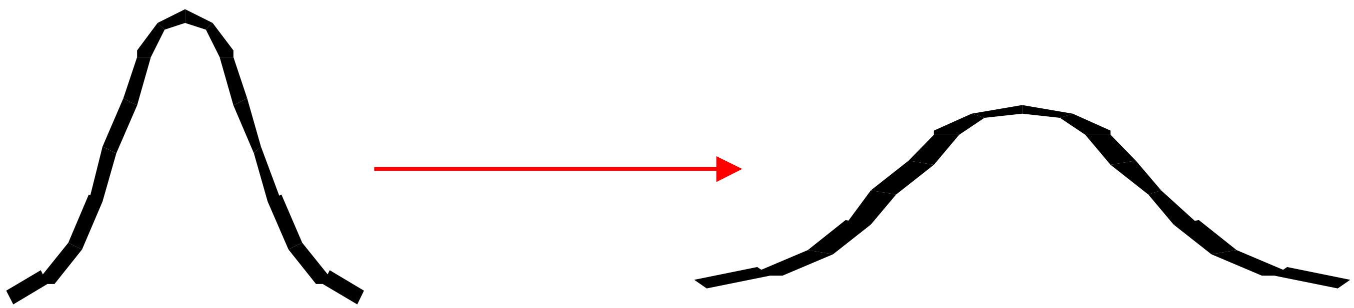
Sensitivity for etched grating





L ~ 200m
without bandgap

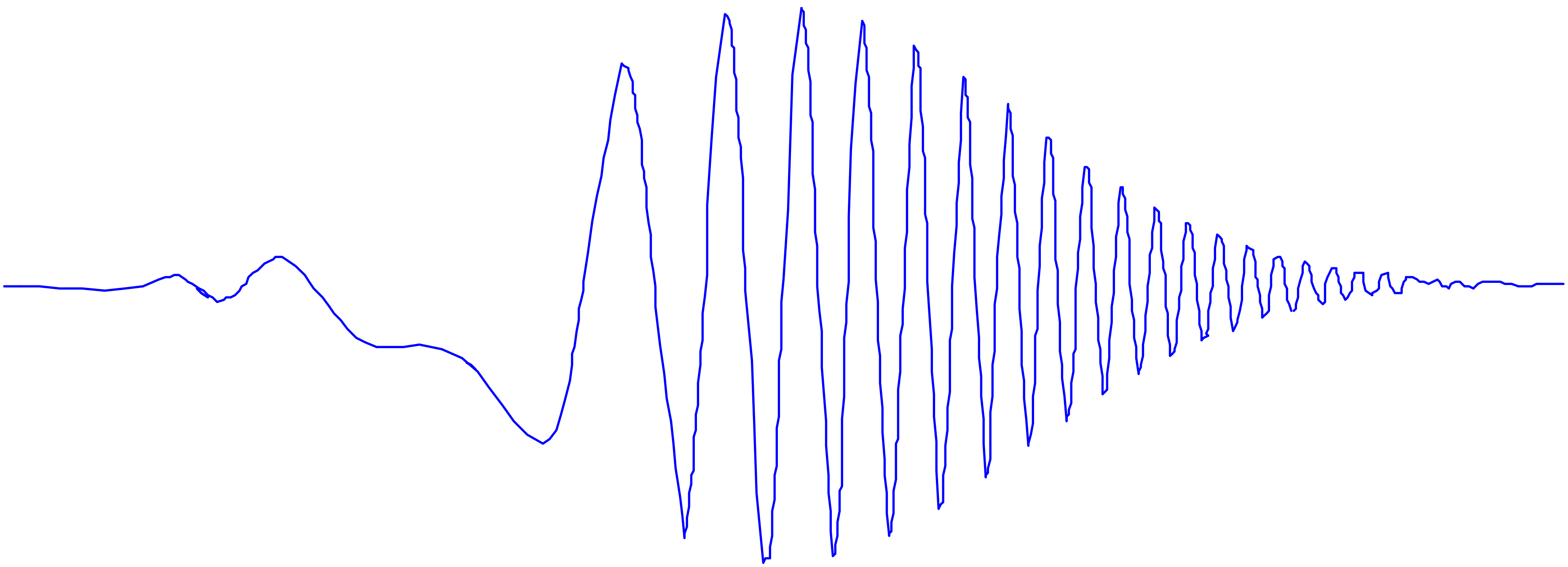
Dispersion and Signal Distortion



$$\text{figure of merit } f = \frac{\text{spreading}}{\text{feature size}} \sim \text{spreading} * \text{bandwidth}$$

$$\sim \Delta T * \text{bandwidth} * \frac{\Delta\left(\frac{1}{v}\right)_{BW}}{\Delta\left(\frac{1}{v}\right)_{\Delta n}}$$

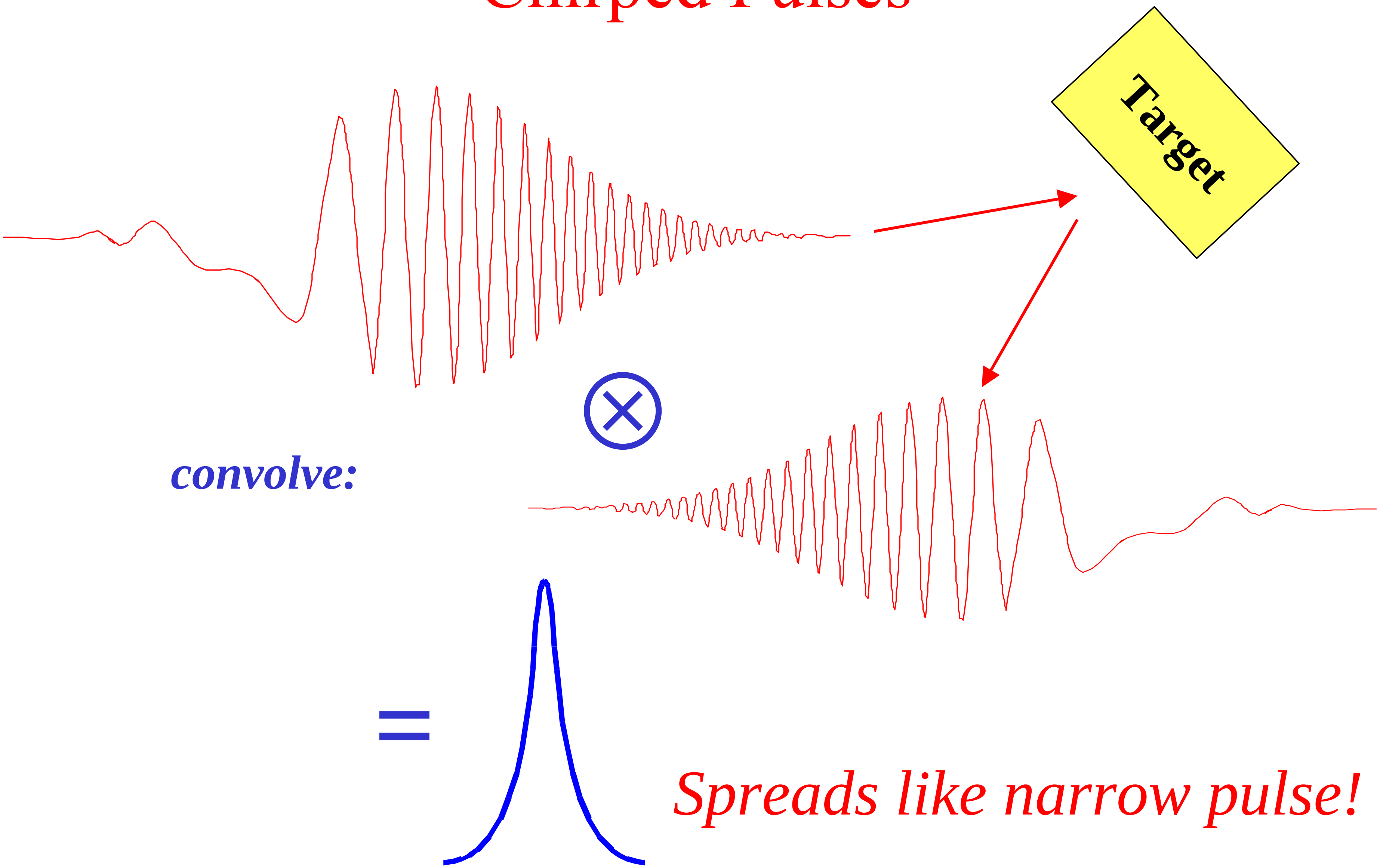
Chirped Pulses



increasing frequency →

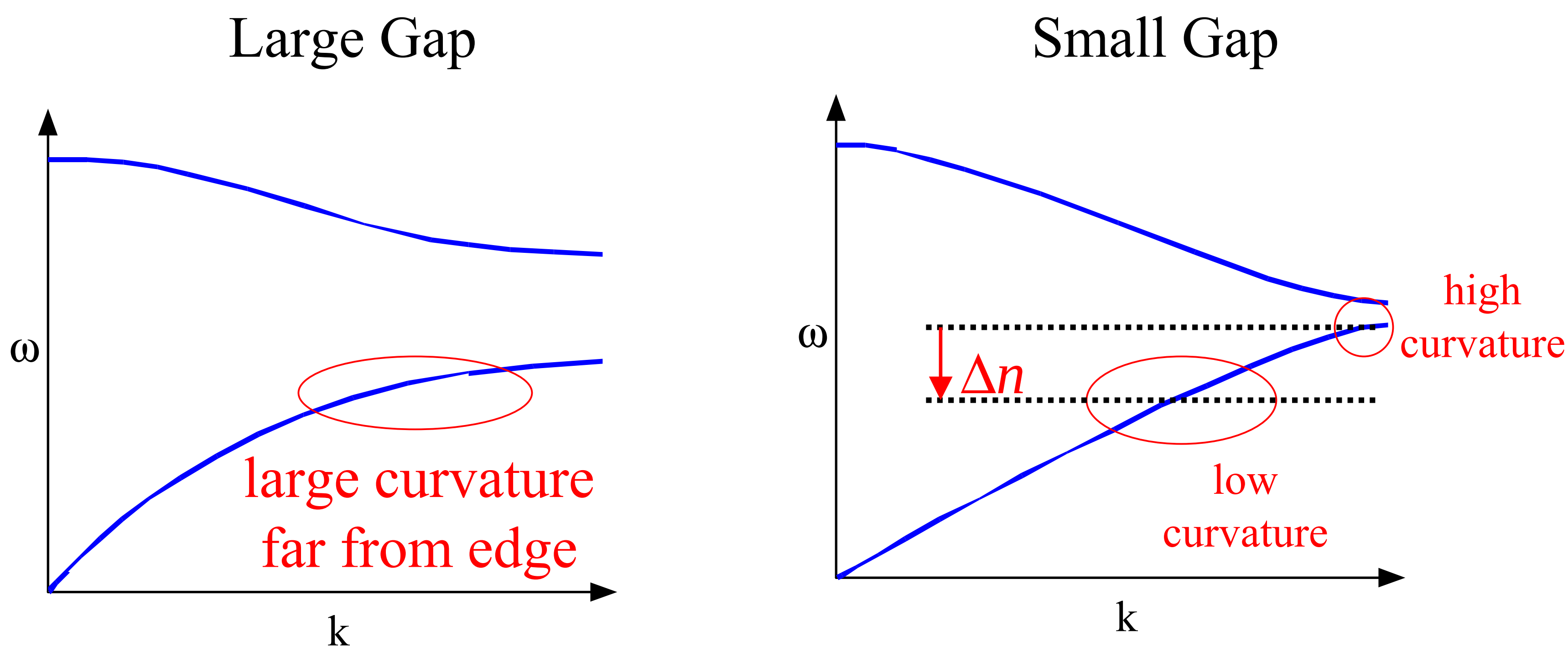
Wide envelope = No spreading

Chirped Pulses



Spreads like narrow pulse!

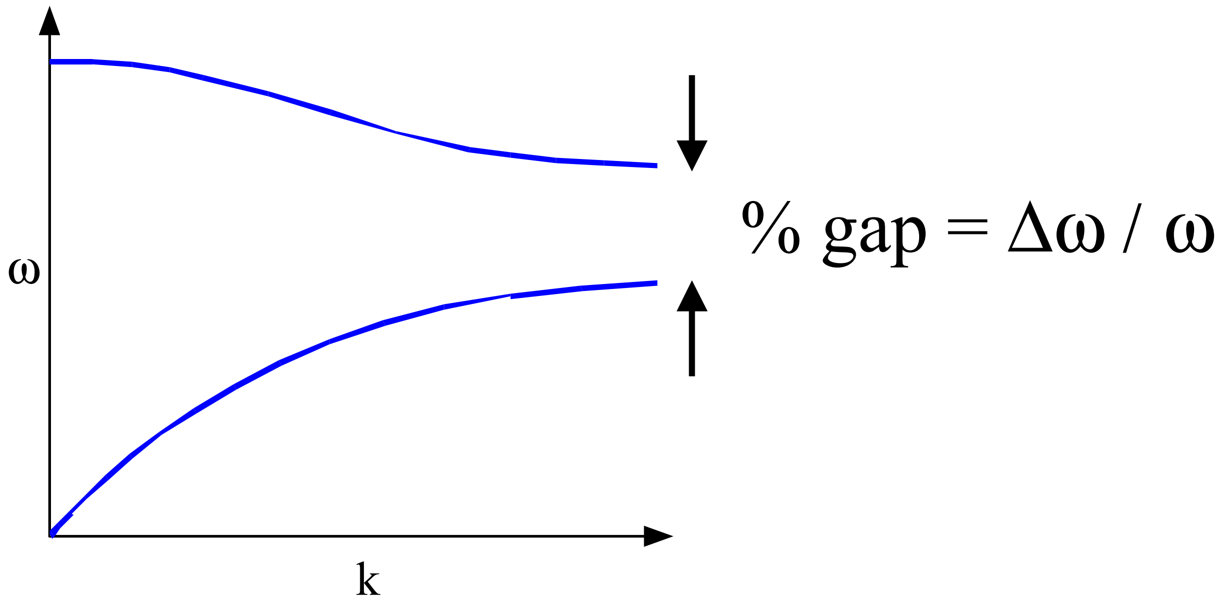
Effects of Gap Size



Large sensitivity for moderate dispersion

Low sensitivity for high dispersion

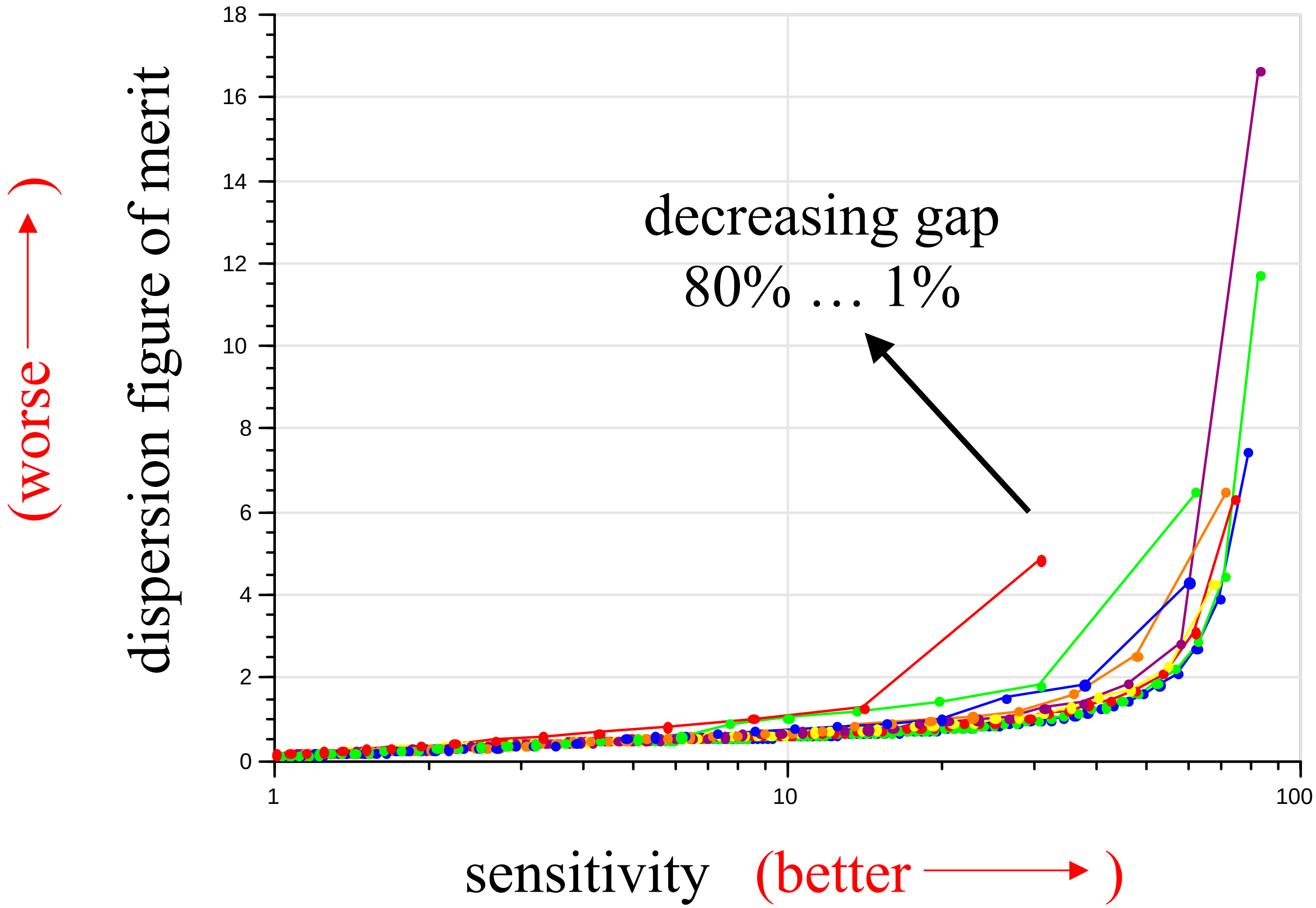
Effects of Gap Size



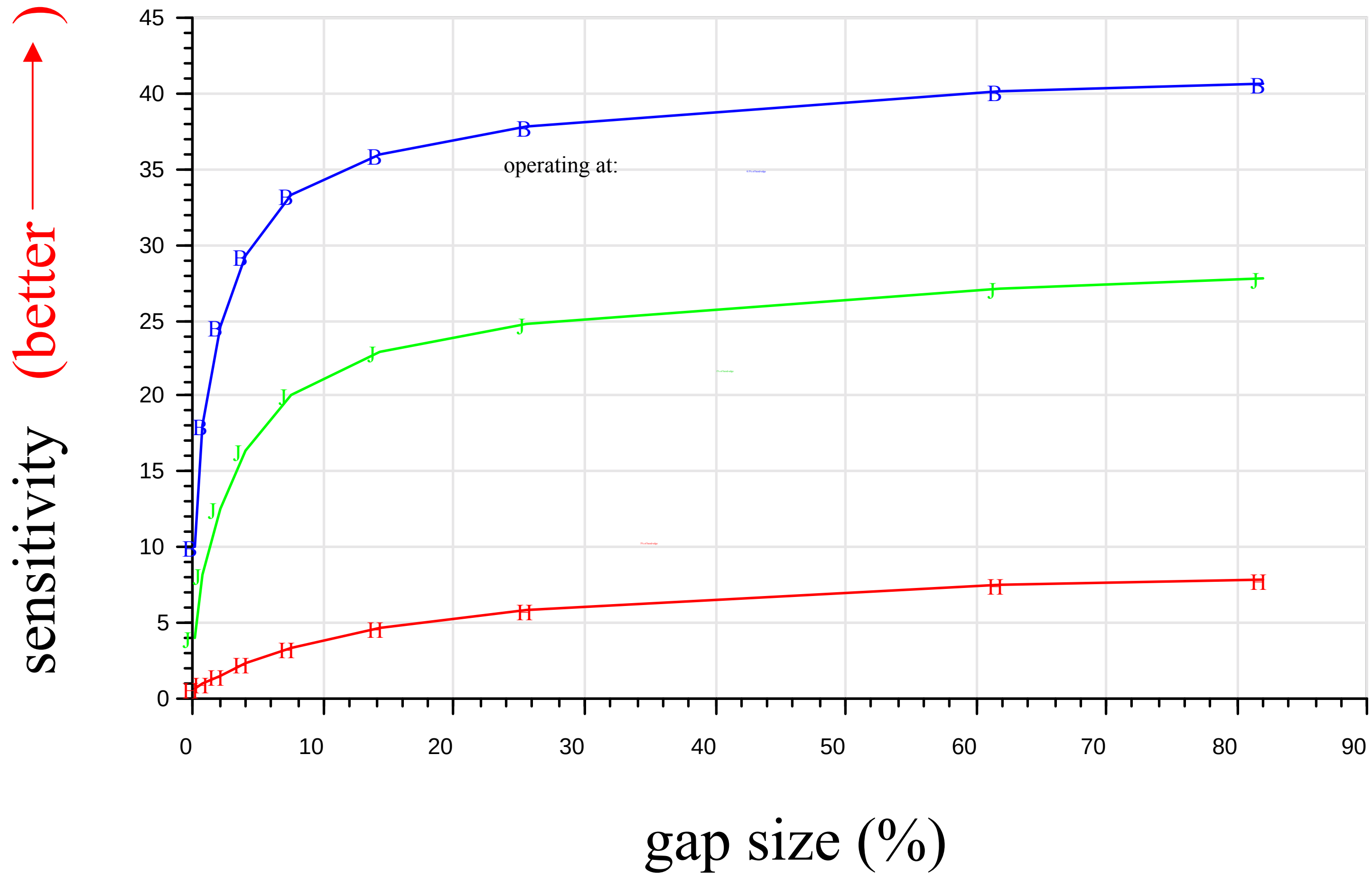
vary gap size, fixed mean index, in 1d system

…analyze sensitivity & dispersion

Worse Dispersion for Smaller Gaps



Worse Sensitivity for Smaller Gaps



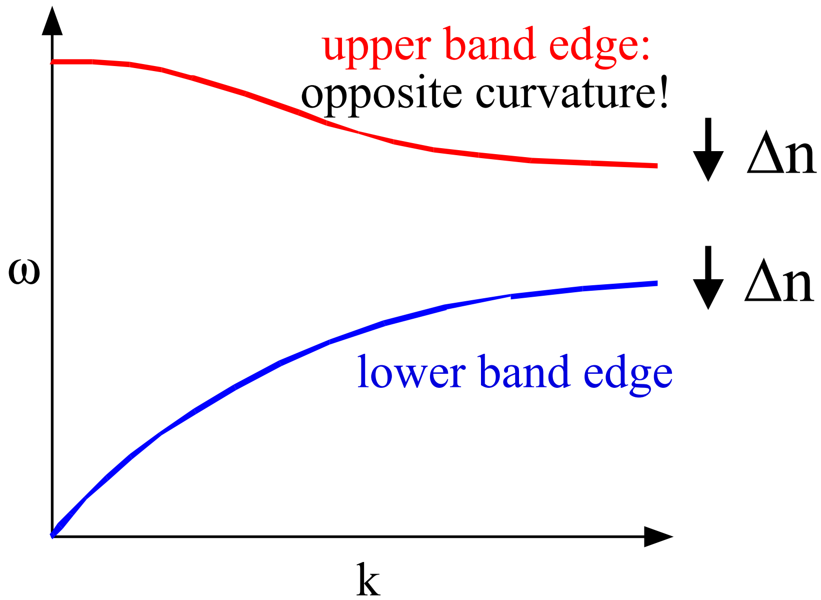
Rules of Thumb:

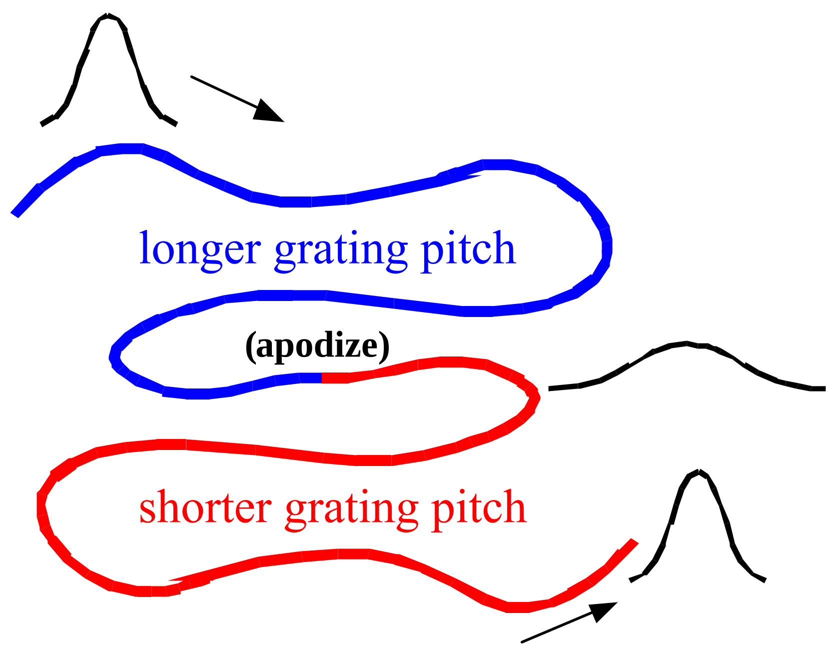
low dispersion: $\text{gap}\ \% \gtrsim \Delta n / n$

high sensitivity: $\text{gap}\ \% \gtrsim \Delta\omega_{edge} / \omega_{edge}$

Another possibility:

Dispersion Compensation





needs
coordinated, opposite tuning
of both band edges

Losses

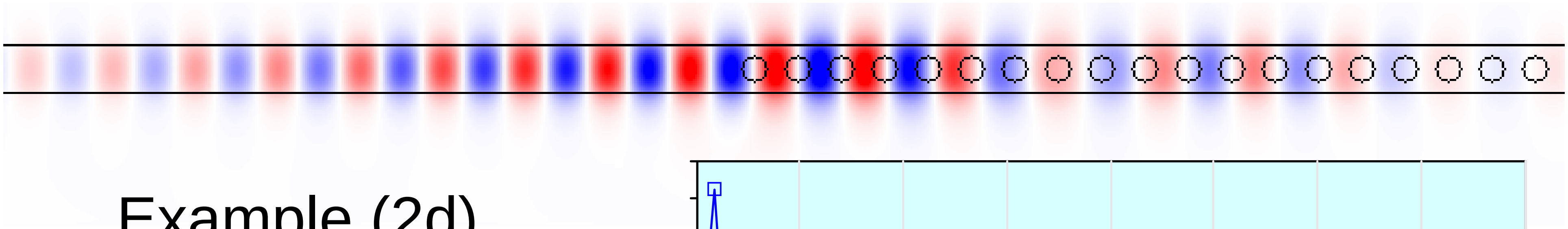
- In/out coupling

- Bends & crosstalk

- Roughness/disorder

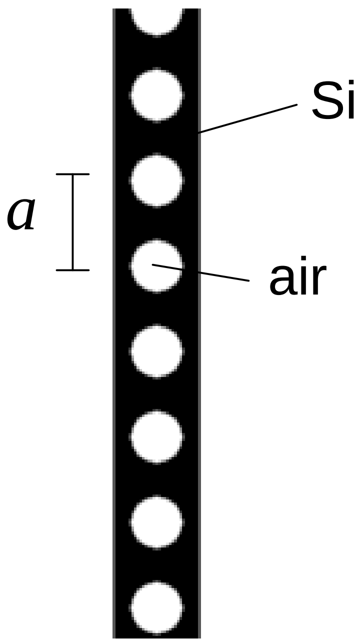
Losses

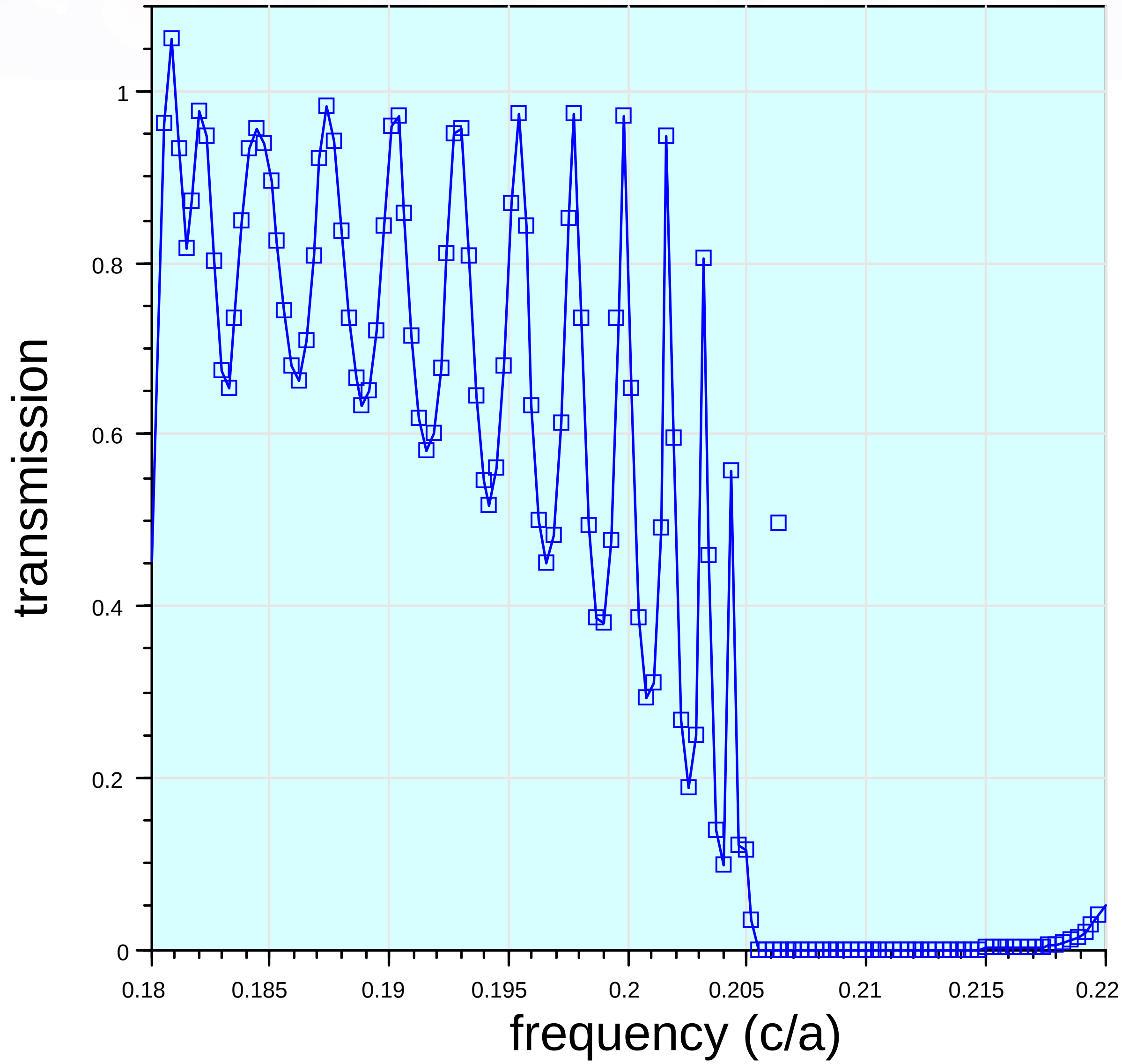
- In/out coupling
  - fiber to chip
  - chip to photonic crystal
- Bends & crosstalk
- Roughness/disorder

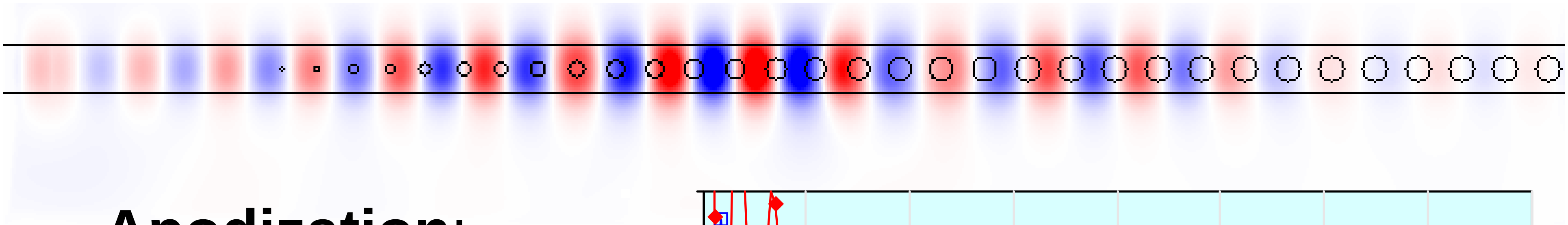


Example (2d) grated waveguide:

Direct coupling is
very poor
near band edge!

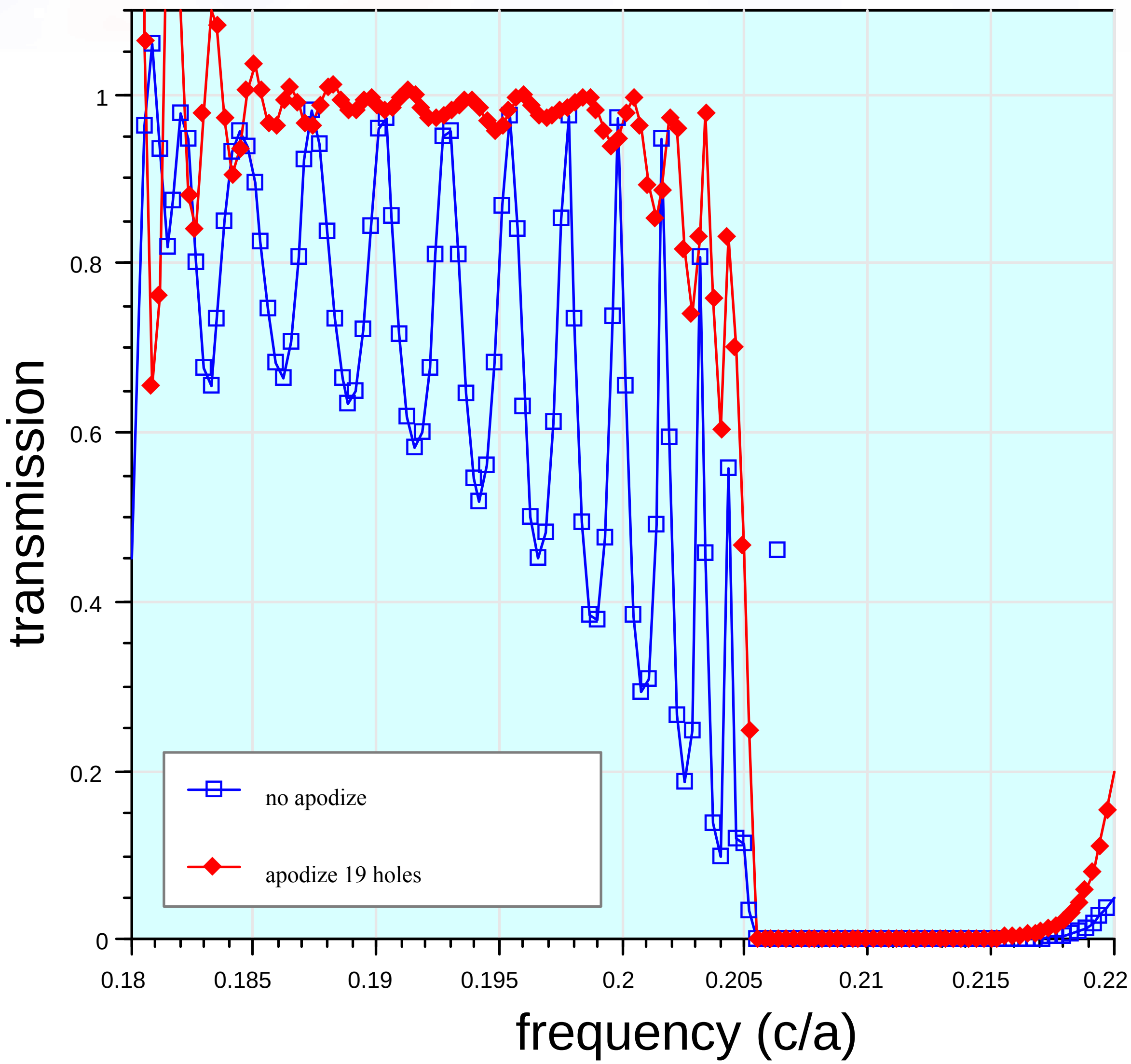






Apodization:

Continuously
“turn on”
grating



Theory:

Can arbitrarily

improve coupling

…with **some conditions**

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Losses

- In/out coupling → fiber to chip
  → chip to photonic crystal

Negligible for ~mm chip size
and strip-like waveguides

- Bends & crosstalk

- Roughness/disorder

Losses

- In/out coupling → fiber to chip → chip to photonic crystal

Negligible for ~mm chip size and strip-like waveguides

- Bends & crosstalk

- Roughness/disorder

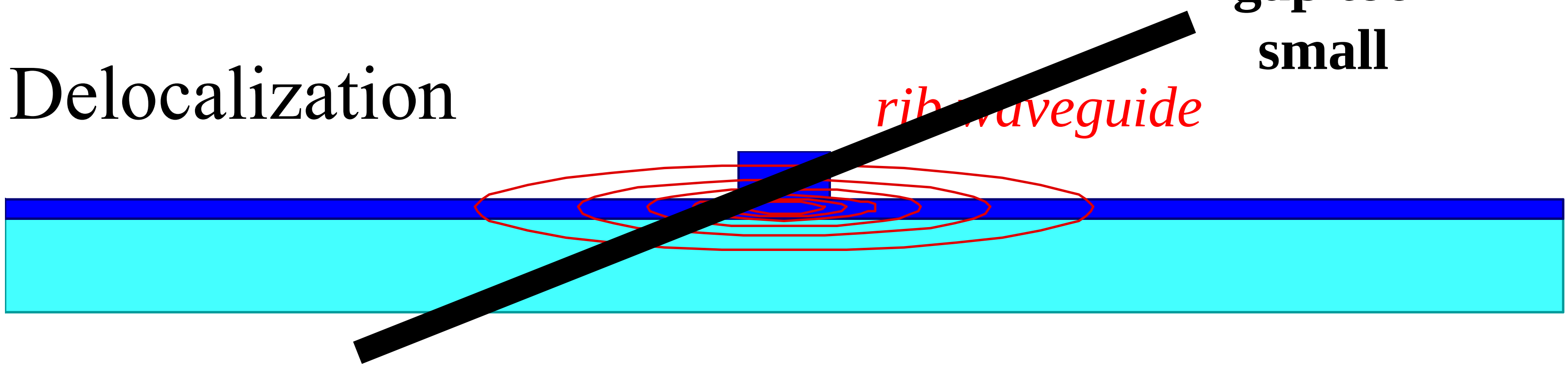
Goal:
< 10dB over ~50ns,
so < 0.2 dB/ns

corresponds to < 0.02 dB/cm in uniform Si

Roughness Strategies

- New fabrication methods
- Reduce tuning range via switching
- Delocalization

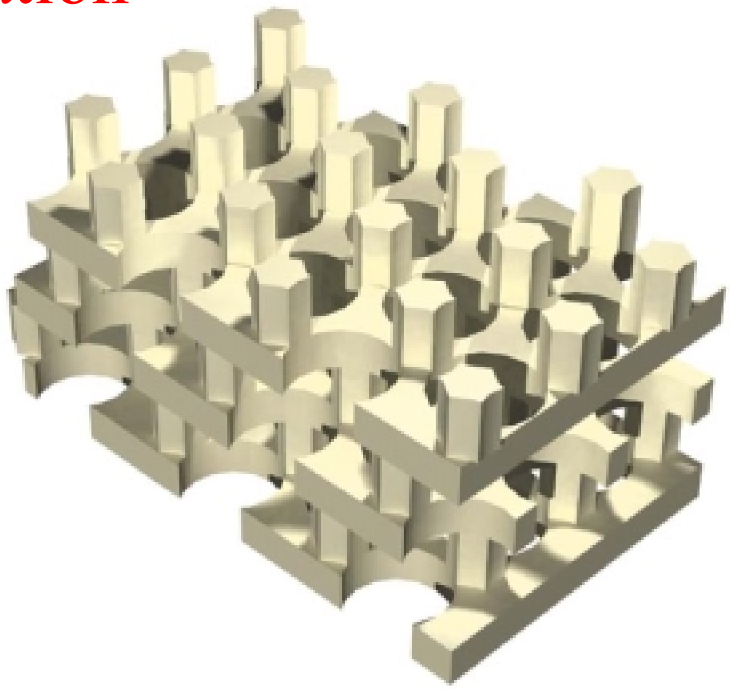
gap too small



- More photonic crystals…

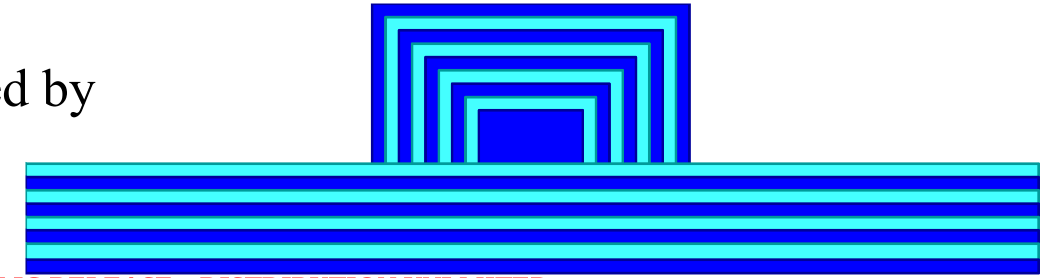
3D crystal can suppress *all* radiation

- only reflections remain
- guide in *air:* larger area



1d/2d crystal can suppress *some* radiation

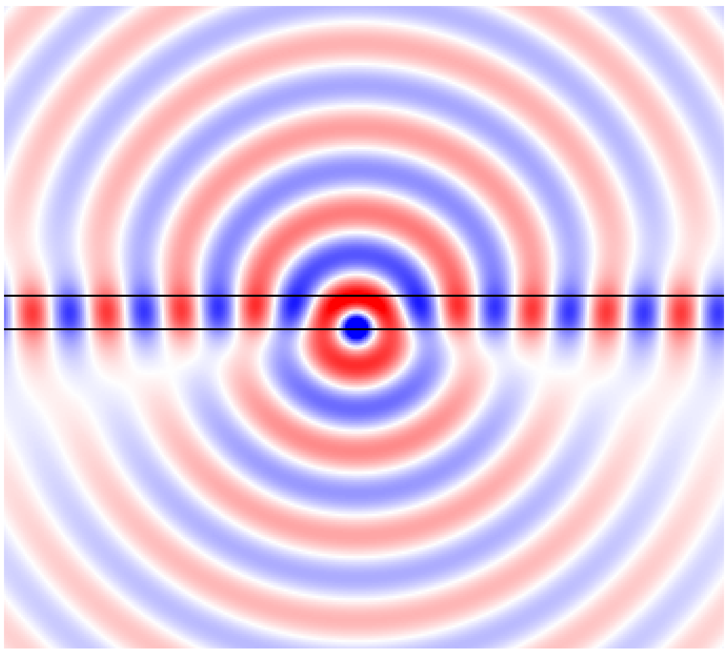
Waveguide surrounded by
1d photonic crystal:



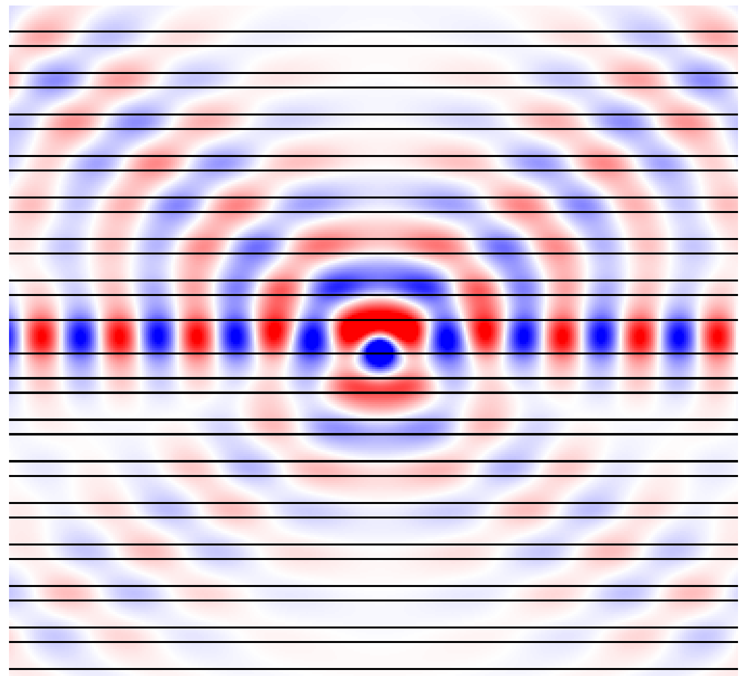
Effect of an *Incomplete* Gap

Radiation from a *point* of roughness in 2D

~ losses from uncorrelated surface roughness



Conventional waveguide
(matching modal area)

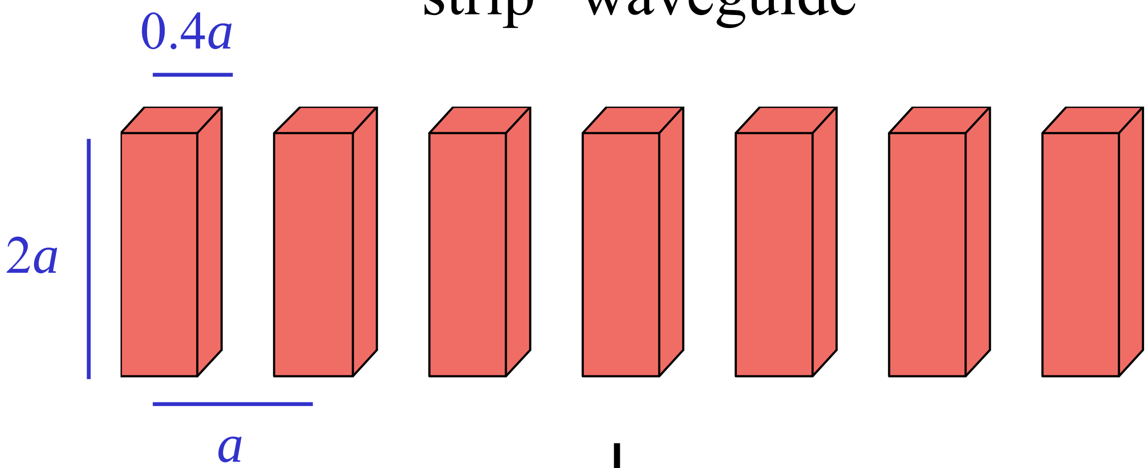


…with Si/SiO_2 Bragg mirrors (1D gap)
50% losses (dB)

Summary

- Delay tunability improves by ~100
- Large gap (& strong confinement) is key
  - for high sensitivity, low dispersion
- Coupling problem well-understood
- Low losses are a challenge
  - photonic crystals can help

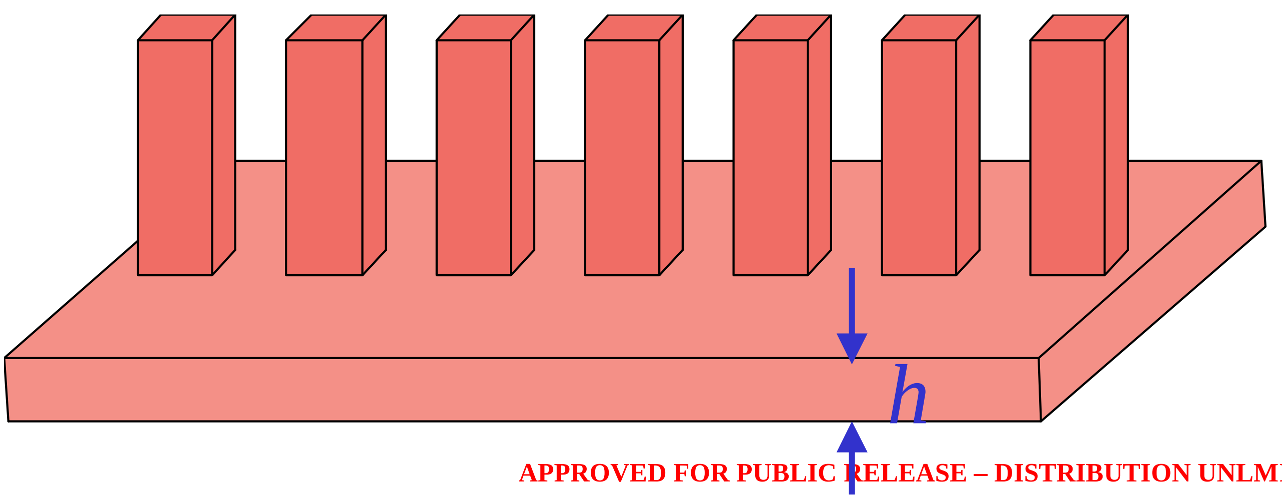
“strip” waveguide



strong confinement

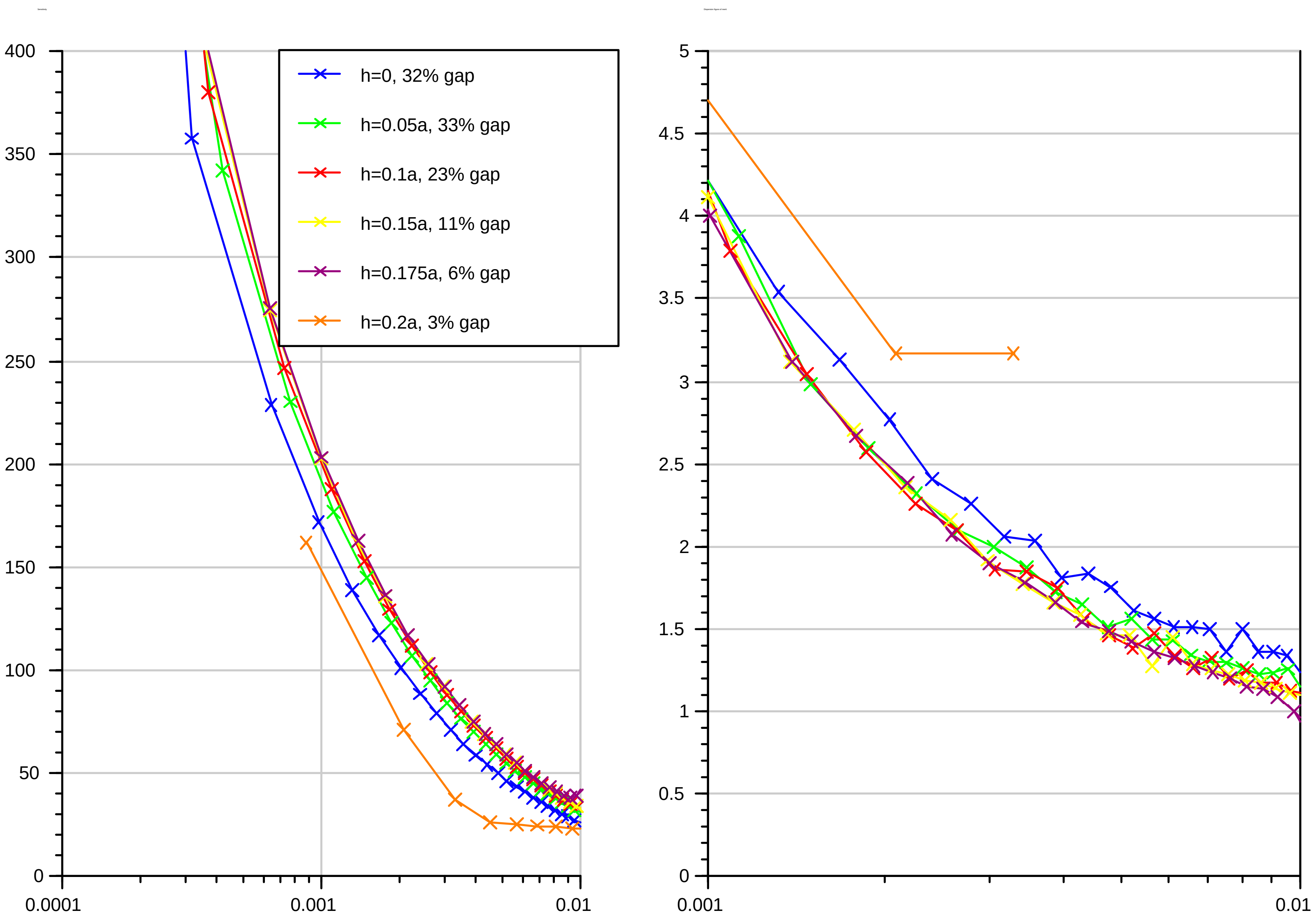
large gap

“rib” waveguide



weak confinement

small gap



²frequency from band edge / band-edge frequency

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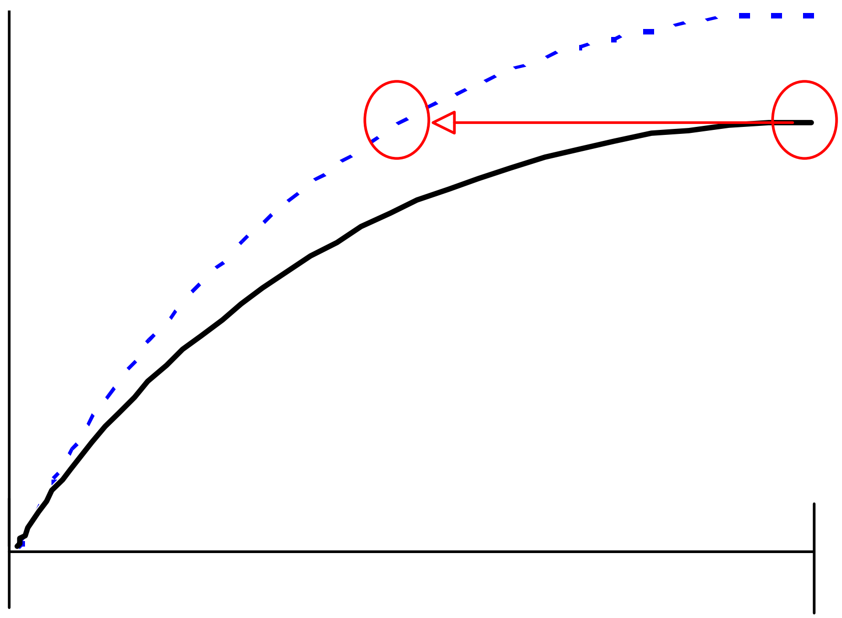
Photonic Crystals
+
Active Devices



low group velocity

=

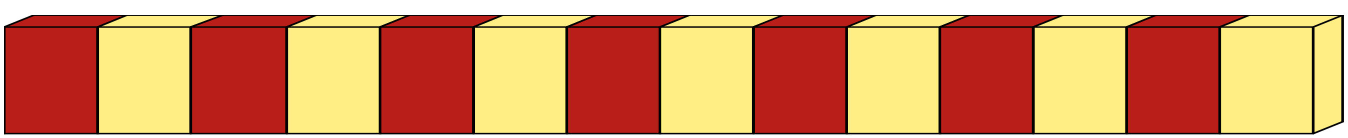
large phase shift / Δn

but

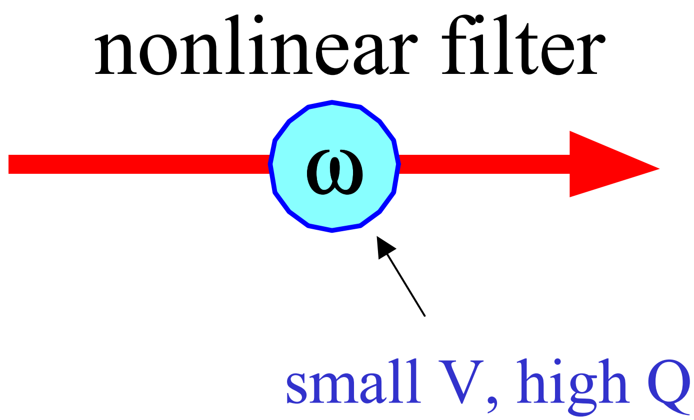
fixed sensitivity * bandwidth

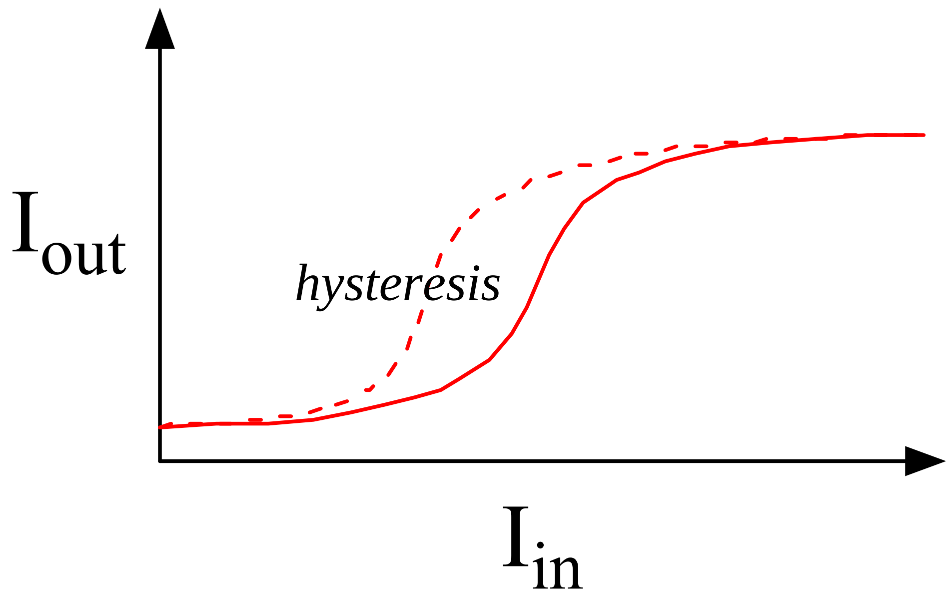
still, reduced size

…lower power



Optical Bistability





optical "transistor" … rectifier, logic, amplifier, *etc*.

threshold power ~ 1 / VQ^2

Theoretical results for photonic-crystal tapers:

- Proven adiabatic theorem:

  slow tapers approach 100% transmission
  …*given simple conditions*

- New coupled-mode theory for photonic crystals

  — efficient modeling of slow tapers in 3d
  … direct optimization of taper rate